# Risk assessment of contaminated sediments downstream of Witwatersrand Gold Mining Operations

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**Abstract** Gold mining in the Witwatersrand has continued for more than a century but has been in decline for some years, with a significant number of mines having ceased operations. The streams draining the goldfields have been contaminated by a combination of point discharges of water pumped from mining operations and decanting to the surface from abandoned operations and diffuse sources, mainly the large waste rock and tailings piles which are a feature of the Witwatersrand landscape.

A combination of airborne radiometric surveying and sediment sampling downstream of these operations has identified elevated radionuclide and heavy metal concentrations. Laboratory methods and an adaptation of the US EPA RAGS (Risk Assessment Guidelines for Superfund) have been applied to this problem to identify and quantify significant risks.

## Introduction

Gold was discovered in quartz-pebble conglomerates on the Witwatersrand in South Africa in 1886. The initial discovery was made on the farm Langlaagte, in what is now the city of Johannesburg and within a few years, the goldfield had been extended along a strike length of more than 100km, extending from Springs in the East to Randfontein in the West. In the decades that followed, additional gold fields, buried under younger cover rocks, were discovered along a strike length of more than 300km (See Figure 1). The Witwatersrand is estimated to contain 45% of the world's gold reserves and has contributed approximately 1.4 billion ounces, 40% of all the gold ever produced (van Tonder 2006). Uranium exploration and production in the Witwatersrand was initiated by the Manhattan project (Winde 2006), with South Africa eventually becoming the $4^{th}$ largest producer of uranium worldwide, with the vast majority of this production coming from the sediments of the Witwatersrand Supergroup (Cole 1998).

The studies presented in this paper have focused on the East Rand, Central Rand, West Rand and Far West Rand goldfields. The first three are the oldest gold mining areas of the Witwatersrand, with gold currently mined underground only in the eastern part of the Central Rand and the East Rand goldfields, while the Far West Rand is a newer gold field, with large-scale mining dating back to the 1960s (van Tonder 2006). There is currently interest in reopening some of the Central Rand mines, with a potential life-of-mine of another 20 years. Most of the gold mining has taken place to the south of a major continental water divide, running in an east-west direction across the area. A small portion of the West Rand Goldfield drains to the north. The area downstream of the gold fields is largely flat lying and underlain by a dolomite unit, which forms a major aquifer, regarded to be a potentially important contributor to the local water supply. Mining in the far West Rand occurs largely below this dolomitic unit, which has been dewatered in this region to allow mining to continue. This generally flat-lying terrain as well as the dolomite, which provides buffering capacity for the acidified mine waters, has led to the formation of large wetland systems, sustained in part by the inflow of water from the mines and from the cities which developed around these mines.

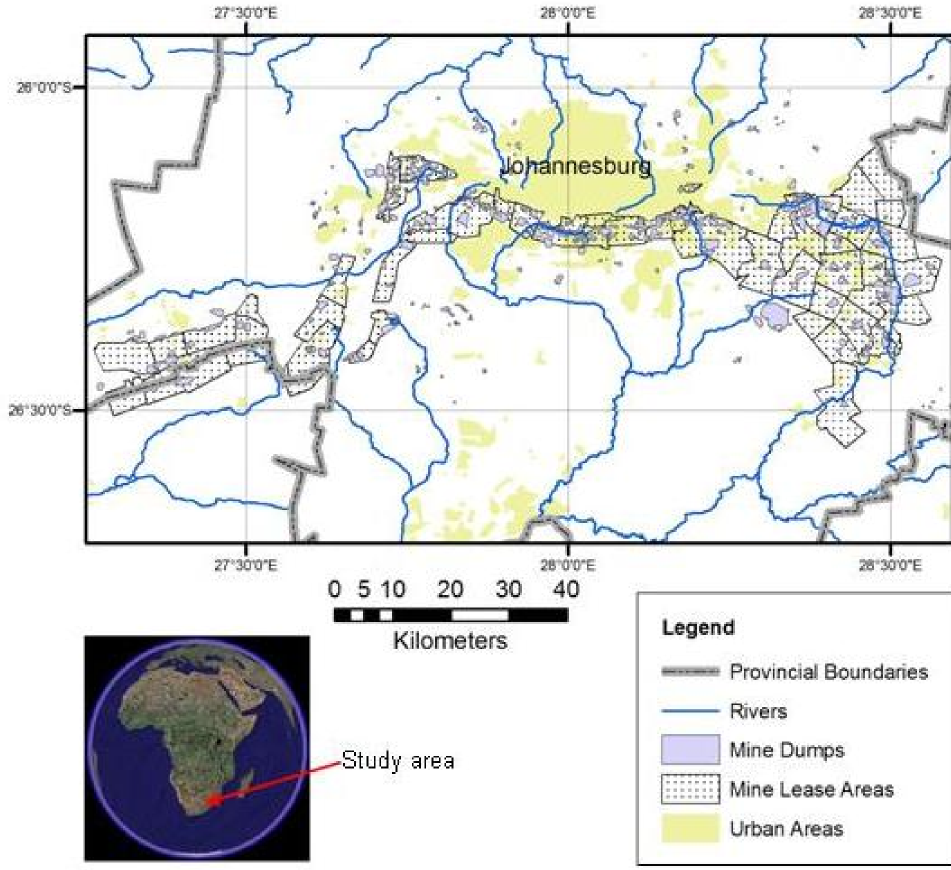


Figure 1. Locality plan, showing gold mines, waste dumps and rivers draining the goldfields

## <u>Contamination of sediments downstream of mining activities</u>

### <u>Contamination sources</u>

The gold ores of the Witwatersrand contain appreciable quantities of pyrite, which oxidises to form acid drainage, which in turn is able to leach metals from the ores and waste piles. In addition to gold, uranium and a number of other metals are found in the ores. Nickel, cobalt, copper, zinc and manganese have all been detected at elevated levels. This same suite of contaminants is also found in the tailings piles, which have become a characteristic feature of the Witwatersrand landscape.

During the development of the Witwatersrand mines, the voids of adjacent mines were connected, allowing access between mines for practical mining and safety reasons. This has led to the formation of large interconnected underground voids, where water can flow from one mine to another. With the closure of mines, this has led to a situation where individual mines now need to dewater these interconnected voids to allow mining to take place within the one mine. Large volumes of water are therefore pumped from underground mine workings. Often this water is contaminated with salts and metals and is generally discharged to the rivers draining the goldfields, usually with treatment limited to neutralisation of the low pH and removal of iron by a combination of liming and aeration. These discharges as well as the diffuse discharges from residue piles constitute a significant portion of the water and salt loads draining to the South from the Witwatersrand mines. Specific pollution concerns which have been noted in this area are the high concentrations of sulphate, iron and radionuclides, with uranium having been identified as a contaminant of concern, largely due to its chemical toxicity (Coetzee and Ntsume 2006; Wade et al. 2006).

In the West Rand Goldfield, underground mining ceased in the1990s. The interconnected mine voids were allowed to flood and water daylighted in 2002 (Coetzee et al. 2005). This water now flows to the north, of the watershed, although much of the water is treated and discharged to the south into the Wonderfonteinspruit, a stream which includes much of the West Rand and Far West Rand Gold fields in its catchment area.

<u>Fate and transport of contaminants</u>

A notable feature of the water quality in these systems is a general improvement in water quality as the water flows through wetland systems. This has been noted in studies of radionuclides (Institute for Water Quality Studies 1999) and has been followed up by Wade *et al.* (2002 ), who recorded high concentrations of uranium-series radionuclides in sediments downstream of mining activities in the West Rand and Far West Rand. Coetzee *et al.* (2005) have noted similar patterns for the Central and East Rand, while McCarthy and Venter (2006) have noted elevated heavy metal concentrations in peat from wetlands in the Klip River, which drains the Central Rand. The principal mechanisms for this contamination of downstream sediments are the mechanical erosion of tailings, which has been observed in many of the rivers downstream of the mining areas, the precipitation of metal-rich minerals in the wetland systems, or the bio-accumulation of metals in the wetland biota. The formation of new minerals has been reported by Coetzee *et al.* (2006), who has noted the growth of framboidal sulphide mineral grains in sediments from a dam in the Far West Rand. The uranium concentrations in many of these wetland sediments also exceed those in the ores and wastes, suggesting that the contamination mechanism must include a means to concentrate these metals.

## Geophysical survey evidence

Since 1991, the Council for Geoscience, South Africa’s national Geological survey, has been undertaking high-resolution airborne geophysical surveys covering the Witwatersrand area. As would be expected for uranium mining areas, the mine residue deposits show significantly elevated activities from the uranium series. Of greater concern however is the elevated count rates seen coming from the wetland sediments downstream of these mines. Figure 2 shows a typical radiometric image of these mining areas. The specific image shows a portion of the Wonderfonteinspruit, downstream of the mining town of Randfontein. Field follow-up of these anomalies has shown significant and unpredictable uranium series disequilibrium (Coetzee and Szczesniak 1993). While uranium contents cannot be determined using this method, the rapid full coverage of large areas provided by airborne geophysical methods allows the identification of all significant radioactivity anomalies within a large area.

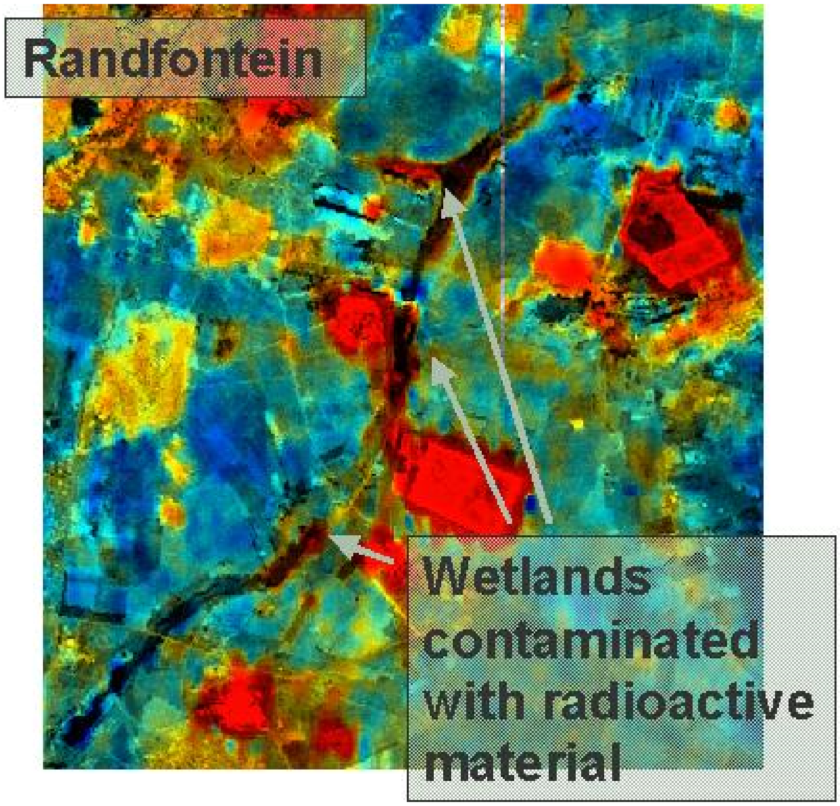


Figure 2. Total count radiometric image of a portion of the Wonderfonteinspruit catchment, over a Landsat image background. Red areas indicate elevated radioactivity levels. Note the elevated radioactivity in the wetlands downstream of mining areas.

## Downstream sediment sampling and analysis

Following the geophysical surveying of large areas of the Witwatersrand, detailed sampling has been undertaken to determine the extent and degree of contamination of wetland sediments. This has included studies looking at:

- The history of contamination as shown in peat cores.
- The degree of contamination, by comparison to regulatory limits.
- Risk assessment, looking at the possibility of re-release of contaminants into the river systems in future.

### The history of contamination

A number of peat cores have been drilled using a hand auger (See Figure 4) from the wetlands in the Klip River system, which drains the Central Rand Goldfield (McCarthy and Venter 2006). These have been subsampled and analysed and in some cases dated, using radiocarbon dating, to determine the age of the base of the sediment pile. Figure 3 shows profiles of the heavy metal contents in three of these auger holes.

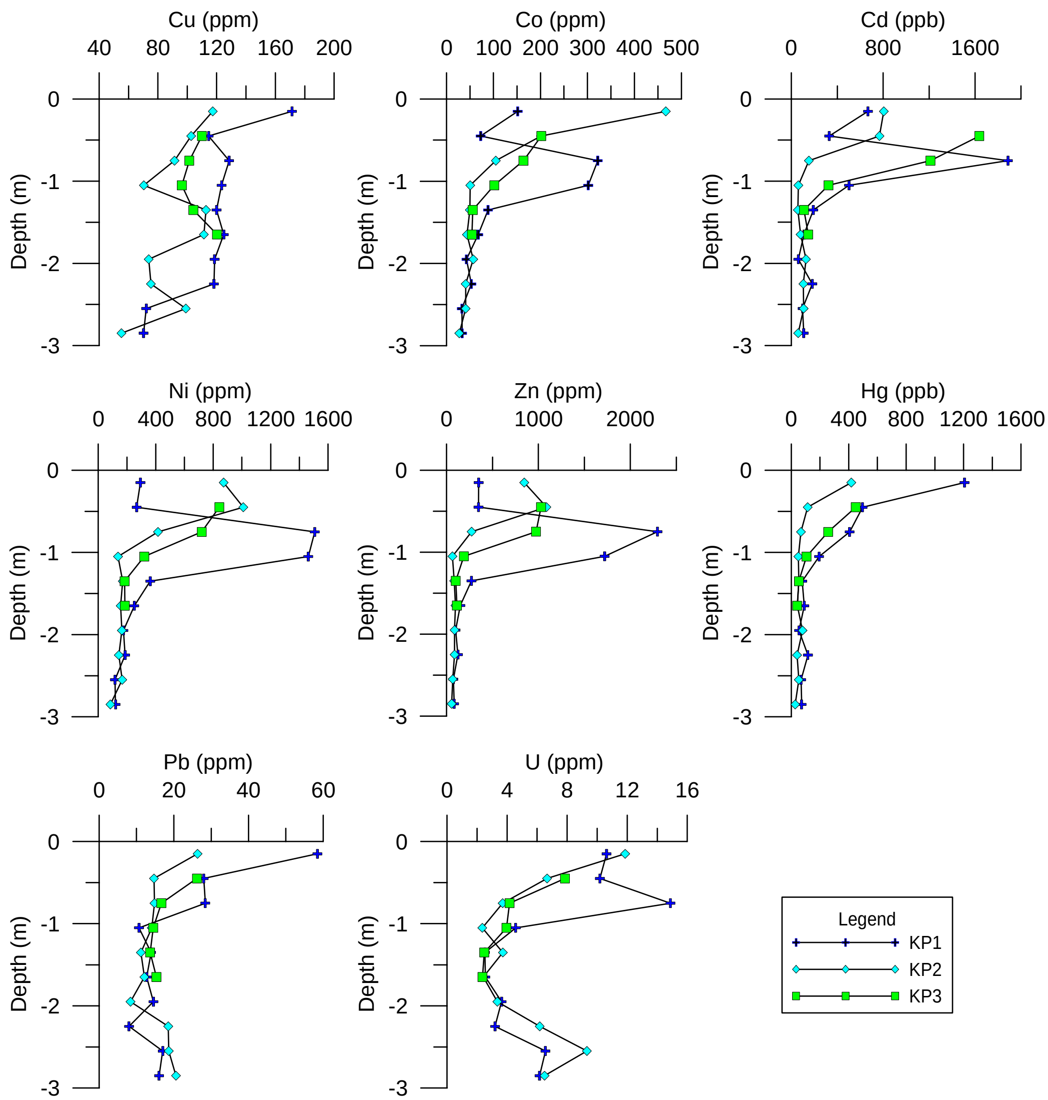


Figure 3. Heavy metal profiles down three boreholes from Wetlands in the Klip River, South of Johannesburg (McCarthy and Venter 2006).

Radiocarbon dating of peat from a depth of 3.0m in borehole KP1 gives an age of 1260±35 years, and from a depth of 2.5 m in core KP2 was 2550±45 years. These ages are to be regarded as minimum ages because of the likelihood of contamination of the oldest sediments with younger roots from the *Phragmites* reeds growing in these wetlands. This is an important result, as it shows that the wetlands have not, as is often stated, grown only as a consequence of the wastewater, sediment and nutrient inputs from the city of Johannesburg, which was established after the discovery of gold 120 years ago. It is important to note however that the contamination is generally limited to the upper half of the cores, suggesting that half of the growth of the sediment pile has occurred since the establishment of the city. Furthermore, contaminants not related to mining, such as phosphate show a similar pattern, indicating that the contaminant load entering the wetland system is not simply a result of mining.

Figure 4. Sampling of peat cores in a wetland in the Klip River

Figure 5. Acid mine drainage entering a wetland downstream of a Witwatersrand mine

Table 1. Tier 1 risk quotients for metals from wetland sediments affected by mining in the East, Central, West and Far West Rand Goldfields

| | **Number** | **Minimum** | **25th Percentile** | **Median** | **75th Percentile** | **Maximum** |
|---|---|---|---|---|---|---|
| Mo | 88 | 0 | 0 | 0 | 0.02 | 0.17 |
| U | 88 | 0 | 0.1 | 0.99 | 2.18 | 31.55 |
| Th | 88 | 0 | 0.02 | 0.03 | 0.06 | 0.33 |
| Pb | 88 | 0 | 0.05 | 0.12 | 0.22 | 1.26 |
| As | 88 | 0 | 0 | 1.54 | 5.26 | 37.2 |
| Ga | 88 | 0 | 0.6 | 1.09 | 1.45 | 2.26 |
| Zn | 88 | 0 | 0.02 | 0.07 | 0.22 | 1.75 |
| Cu | 88 | 0 | 0.2 | 0.76 | 1.52 | 14.51 |
| Co | 88 | 0 | 0.13 | 0.51 | 1.52 | 36.19 |
| Ni | 88 | 0 | 0.39 | 1.5 | 4.93 | 68.75 |
| Cr | 88 | 0 | 0.46 | 0.67 | 0.95 | 2.79 |
| V | 88 | 0 | 0.93 | 1.48 | 2.06 | 3.97 |
| Ba | 88 | 0 | 0.2 | 0.28 | 0.4 | 1.72 |

The degree of contamination

Coetzee *et al.* (2005) have identified nickel, arsenic, uranium, copper and cobalt as being generally elevated above environmental guideline or limiting values in wetlands across the entire study area. A summary of tier 1 risk quotients

(Environmental Protection Agency 1997; Servant 2002) for the elements analysed are presented on **Error! Not a valid bookmark self-reference.**. These are calculated by dividing the measured concentration by the legislative/regulatory limit for that contaminant.

$$\text{Risk Quotient} = \frac{\text{Measured Concentration}}{\text{Legislative/Regulatory Limit}}$$

Values greater than unity indicate follow-up investigations which could lead to remedial action.

Risks due to re-release of contaminants

Although the wetlands to the south of Johannesburg appear to play an important role in the amelioration of pollution problems, one of the key questions regarding this role is whether or not the process is reversible. In order to assess the risk that the contaminated wetlands may pose to downstream water users, a number of studies (Wade et al. 2002 ; Coetzee et al. 2006) have performed sequential extraction analyses on contaminated sediments and Wade *et al.* (Wade et al. 2002 ) has studied the speciation of radionuclides in river waters from the Far West Rand.

The sequential extraction studies rely on the simulation of plausible environmental (Eh and pH) conditions (Tessier et al. 1979). A sample of sediment is exposed sequentially to an increase in ionic strength, acidic conditions (See Figure 5), reducing conditions and oxidising conditions, and the concentrations of contaminants are measured in the resulting leachates. These can be related to environmental conditions as described in Table 2.

Table 2. Environmental conditions simulated in sequential extraction experiments

| **Extraction stage** | **Environmental conditions** |
|---|---|
| Extract A – Increase in ionic strength | Increase in salinity due to additional pollution load |
| Extract B – Mildly acidic | Acidification due to acid mine drainage<br><br>Acidification due to acid rain |
| Extract C – Mildly reducing | Reducing conditions due to inflow/spill of raw or partially treated sewage<br><br>Reducing conditions due to eutrophication |
| Extract D – Mildly oxidising | Drying of sediment due to changes in the flow regime, attempts at mining, or drought after cessation of pumping activities by active mines |

The first extraction stage, increasing the ionic strength of the solution, has been shown to not extract significant quantities of heavy metals and radionuclides from the sediments, while all other stages extract these metals. The implication is that any of the environmental conditions that these experimental stages simulate could result in the release of metals from the sediments and a consequent negative impact on downstream water quality.

## Conclusions and implications for the medium- to long-term future

The wetlands downstream of Witwatersrand mines have been shown to play a significant role in the removal of pollutants from the water which flows downstream from these mines and the cities which have grown up around them. While this has a positive impact on downstream water quality, the accumulation of heavy metals and radionculides in these sediments is cause for concern. Laboratory simulations suggest that changes in the chemical conditions currently active in the wetlands could lead to the remobilisation of these contaminants with a negative impact on downstream water quality.

As the mines of the Witwatersrand enter their closure phase, a real risk exists that they will become abandoned or closed without giving sufficient attention to off-site pollution legacies. In areas where river flow is maintained by the pumping of water from deep mines, a period of low and possibly seasonal river flow will be expected while the mines flood, which could lead to the drying out and oxidation of the downstream sediments. After mine flooding, the possibility of a decant of acid water into the surface streams exists, which could also lead to the re-release of contaminants from wetland sediments.

For these reasons, it is recommended that mine closure plans and strategies take cognisance of possible off-site pollution legacies and that the institutional memory of these issues be preserved in state and statutory organisations, to allow prediction, prevention and, if necessary, appropriate remedial action for possible pollution problems in the future.

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